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Laurence P. Madin, Chair
Department of Biology

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ABSTRACT

Calls of killer whales, <u>Orcinus</u> <u>orca</u>, were analyzed using computed sound features to classify sound patterns and identify call similarities. Calls were classified and separated according to the pod/family group within clans identified previously by John Ford (U. BC) in the Vancouver whale populations. Acoustic characteristics of the same call type from different individuals were extremely similar, so that discriminating these different sounds was the goal. The WHOI AcouStat program and associated database systems were used to define numerical statistics for each call, and then, these were compared to sort and classify the sounds. The results were in agreement with Ford's descriptions of the calls derived from visual inspection of sound spectrograms of calls. The classification analyses demonstrated that although specific shared calls from different killer whales were much alike, they could be sorted by the pod/subpod of the whales producing the calls. A typical analysis, for example, of the N4 call from Clan A (Vancouver, BC), classified 97% of the calls correctly according to the pod/family of the whales producing the calls. Remaining calls were variant, and likely a result of individual differences in call sounds. Similar classification analysis were tested on unsorted, unanalyzed recordings from different populations of whales, and these too could be distinguished, with 98.5% correct separation of the calls.

BACKGROUND

The sounds used by killer whales, Orcinus orca (Linné) 1758, include a variety of click sounds used for echolocation and tonal calls used for communication (Schevill and Watkins 1966). These calls mostly appear to be formed by a pulsed sound mechanism insonifying particular resonances. Therefore, the calls generally are characterized by regularly spaced harmonics and sidebands of the pulse modulation, along with resonant tonal components. Calls have a strident aural quality, usually containing two or more tone segments at variable frequency and pulse modulation, often with shifts in the pulse-rate modulation between components, as well as short chirps of rapidly changing frequency.

The first notice of sounds produced by killer whales appears to have been by Grieg (1907) who described the catching of 47 whales which had produced "flute-like sounds and roars". The earliest recordings of underwater sounds of killer whales (Schevill 1964, p. 313) were made by the Royal Canadian Navy in June 1956 along the west coast of the Queen Charlotte Islands, and on 19 February 1958 in Saanich Inlet, Vancouver Island, B.C., as well as by the U.S. Navy in Dabob Bay, Hood Canal, Washington on 20 October 1960. Valdez (1961) described click sounds from killer whales heard by ear through the hull of his boat, and his recording of these sounds on an echosounder was

the first published reference to hearing this species underwater. Then, on 16 July 1964 the Vancouver Aquarium captured a young killer whale in the Strait of Georgia (Neuman 1964, 1964a) and its underwater calls were recorded by Patrick McGeer of the University of B.C. Schevill and Watkins (1966) also recorded the sounds of this whale from 14 to 18 August 1964, demonstrated its use of echolocation, and analyzed the structure and directionality of its sounds.

Since those early observations, many studies have shown that killer whales are organized in related clans and pods, that all or most members of a clan share calls that are specific to that clan, and that different pods appear to use different clan or pod-specific calls (Ford and Fisher 1982, Ford 1984, 1989, 1991, Strager 1995). The determination of the similarities and differences among these sounds has been accomplished mostly by visual inspection and comparison of spectrographic portrayals of the calls.

The development of a comprehensive collection of sound recordings and databases of marine animal acoustic files at the Woods Hole Oceanographic Institution (WHOI) allowed comparisons and categorization of sounds produced by different species (Watkins et al. 1992, Fristrup et al. 1992). With approximately 70 species of marine mammals represented in these acoustic database files, it was useful to develop a means for computer

analysis of sounds with appropriate sorting to distinguish calls from different species. The system that was developed for this emulated the results of standard spectrographic protocols for bioacoustics (such as that of the Sonagraph by Kay Elemetrics and similar spectrographic equipment). The WHOI system that developed included a comprehensive database organization, FFT analysis, noise compensation, convenient retrieval of digital acoustic sequences, and display and export of spectrographic displays of these animal sounds (Fristrup et al. 1992). A classification system was developed, then, for distinguishing sounds based on calculated sound features expressed numerically (Fristrup and Watkins 1992, 1994) to allow computer organization and statistical comparison among these sounds. These techniques were used to distinguish and classify sounds from different species repertoires in the WHOI sound databases.

Therefore, this approach was considered as a means of discriminating characteristic features and comparisons among the shared pod-specific calls of killer whales. Such calls apparently were sets of nearly identical sounds produced by the different members of a pod. Analysis of these sounds was considered to be a rigorous test of the classification system. Then, if these techniques could define similar patterns of shared calls of other populations of killer whales, they also

might help define relationships among individuals and groups of killer whales, based on the acoustic features of their sounds.

The first step toward this was to refine our classification system and demonstrate that it could distinguish differences among the very similar pod-specific calls of killer whales.

METHODS

Killer whale sounds recorded from a variety of populations were reviewed to compare general characteristics of the sounds produced by this species. Apparent distinctions were noted among call types from whales of different regions (frequency range, call durations, etc.), and similarities were observed that seemed to distinguish this species readily from others (pulsed tonals, segmented calls, etc.).

Recordings of killer whale sounds that had been identified previously as typical of pod-specific calls from particular, well-studied populations were contributed by John Ford and his associates (U. B.C. and Vancouver Aquarium). These included pod-specific sounds from several clans, with identification of the clans, pods and families of the whales producing the sounds, as well as details of their recording. Most of the recordings were provided as digital files, often with accompanying spectrographic representations that allowed recognition of the acoustic call categories assigned to each call.

These pod-specific sounds were in a variety of formats, so that they all required special conversion to the standardized digital sequence of the WHOI sound analysis and database protocols. The design of the conversion programs to change each data file was a first, surprisingly complicated, step.

The specific calls produced by different pods then were catalogued, annotated, and organized within the database system to allow retrieval of calls individually or in selected batches for analysis and comparison. Approximately 200 files were arranged as basic sets of calls for use in calibration of the sound discriminations provided by the classification system.

The sounds within each category of pod-specific calls frequently were nearly identical to those of other pods in a clan. Such sounds were extremely similar acoustically, so much so, that they often could not be differentiated aurally or by visual comparison of spectrographic analysis portrayals. The calls provided by Ford were identified by the call type, and related to the family/pod of the whales producing the sounds. Identification of these family relationships among the whales was by means of the visual inspection of natural marks on the whales at the time of recording.

Analysis and classification --

The analysis and classification systems for these comparisons used our established laboratory acoustic programs, including the WHOI databases of marine animal sound recording libraries, and annotated files of specific vocalizations. These included analysis protocols for measuring acoustic features of sound sequences using the AcouStat algorithms developed by Fristrup (Fristrup and Watkins 1992, 1994, Fristrup 1995) and adapted for use in these assessment of killer whale calls by DiMarzio and Watkins. The whale calls were organized by database for ease in analysis and comparisons (Watkins, Daher, and Haley 1988; Watkins, Fristrup, Daher, and Howald 1992). Whale calls were compared, sorted, and classified to relate acoustic similarities. This classification system using AcouStat involved FFT analysis, dynamic noise compensation, and calculation of quantitative, numerical sound features of the acoustic sequences in each call (features listed in Table 5). These numerical sound features were used to relate calls by means of statistical analyses.

The sound classification analyses involved interrelated steps to measure acoustic relationships among sounds, providing numerical results that could be compared readily by computer (Fristrup and Watkins 1992, 1994, 1995; Fristrup et al. 1992, Watkins et al. 1991, 1992). The following steps were involved:

-- 1) Sound sequences were digitized in the format compatible to those used by the WHOI analytic systems and databases (Fristrup et al. 1992).

-- 2) Calls were identified and organized by databases for ease in sorting and retrieval (INMAGIC database, Cambridge MA).

-- 3) Particular digital sound files were selected from the database for analysis and comparison.

-- 4) Each file was analyzed by overlapping FFT (Fast Fourier Transform) computation (AcouStat algorithms).

-- 5) The overall spectral information from this analysis for each file was assessed and noise backgrounds compensated dynamically to reduce effects of different recording backgrounds (AcouStat).

-- 6) The spectral data were analyzed to calculate approximately 120 numerical acoustic statistics (listed in Table 5) that described each sound (AcouStat).

-- 7) Acoustic feature statistics were organized by database (PARADOX 5.0, Borland, Scotts Valley, CA) and selected for appropriate comparisons of the relationships among sounds.

-- 8) These sound statistics (numerical definitions for each sound file) were compared by statistical analysis routines, such as those of S-PLUS (Statistical Sciences, Seattle, WA).

-- 9) Results of these analyses and classifications (cluster analyses, tree diagrams, etc.) were compared with the sound data and file identification attributes.

-- 10) Spectrograms of selected calls allowed assessment of gross variations among the identified groups of acoustically similar calls, and confirmed differences in sound classification parameters.

New calls were incorporated into sequential analyses to further delineate call similarities and sort call groups. As recordings of calls became available, they were made into separate digital sound files and integrated into the database system, their acoustic features were calculated, and they were compared with previous killer whale sound data. The file conversions and database organization of calls (steps 1 and 2) proved to be the most time-consuming. The acoustic measurements and feature calculations (steps 3 to 7) were by iterative computer programming. The detailed comparisons and statistical analysis of feature defined calls (steps 8, 9, and 10) provided assessments of call similarities and distinctions.

Statistical analysis --

Statistical analysis of the killer whale calls was performed to provide means of classifying calls into groups with nearly identical acoustic characteristics, and distinguishing calls that were different. For example, classification trees compared the sets of AcouStat sound features for the different calls using analytic software such as S-PLUS (Statistical Sciences, S-PLUS guide to statistical and mathematical analysis, Version 3.2, Seattle: StatSci, 1993). In S-PLUS, the statistical model for the classification tree compared particular response variables with sets of identified predictors.

Thus, the response variables for such an analysis of the Vancouver killer whale data used the shared pod-specific call types (as identified by Ford, such as, the N04, N03, N11 call categories). The predictors for this analysis used all, or only selected ones, of the 120 AcouStat sound feature statistics for each call (Table 5). These selected predictor variables (sound features) were used by the classification tree algorithm to compare with the different response variables (call types) and create a classification tree. The S-PLUS classification and regression tree analyses were used to compare structure in the data sets. The tree algorithm sequentially assessed values for different response variables and related them to sets of classification or predictor variables.

During these analyses, data sets were recursively partitioned into groups of sufficiently homogeneous data. At each split, or node, in the resulting binary tree, all predictor variables (sound feature statistics) for each sound were examined and compared, and a primary variable was selected to divide the data into two sets. These were then successively analyzed and separated again at each node into consecutively "purer" sets of data. The purity of the data at each node was determined and indicated by the statistical analysis as a "deviance" measure.

At each split in the classification tree, the predictor variable which was most responsible for minimizing the deviance of the two resulting sets of data was identified and used. The process of separating these data ended when all data in a node were either sufficiently homogeneous, or when there were too few sets (usually set to five) to generate another split. For classification of the killer whale data, all of the calls were identified at each intermediate node along with the fractions that were separated. The compositions of these final nodes were indicated, providing the association of sets of calls based on the similaritise of their acoustic characteristics (sound feature statistics).

RESULTS

Our acoustic analysis and classification systems were successfully adapted for use with the extremely similar shared calls of killer whales. Analysis routines were devised for computer differentiation of the calls and allow for assessment of these small variations in sound characters. The classification system was directed toward identification and definition of similarities and differences in the sounds.

The shared sounds from specific pods of killer whales of Vancouver/Puget Sound (ie., Ford 1991) were analyzed and classified according to their acoustic similarities. These shared calls produced by different members of the same family/pod were extremely similar, often not separable by ear or by visual inspection of the display of their spectral analyses.

The classification analysis consistently sorted these shared calls accurately across clans, separated the calls by pod/subpod, sorting the sounds to confirmed that calls from the closest relations were most alike. The killer whale calls were separated acoustically in exactly the same groups, as those indicated by Ford from the field identifications of the whale clan and pod/subpod associations during recording.

These classification results showed the degree of similarity within the different pod-specific call types, as well as the

variation in vocalizations from different pods and families (i.e., Ford 1984, 1987; Watkins, Fristrup, and Daher 1991). Definition by the classification system of these sound distinctions allowed accurate sorting of call types and quantification of their acoustic differences.

Sounds were analyzed from a variety of call types produced by different clans and pods. The classification system based its decisions on acoustic similarity, and these call groups consistently coincided with the clan/pod/family relationships identified during recording of the whales.

Differences in background sounds on these recordings resulting from variations in ambient noise and dissimilar recording systems were effectively eliminated by the analytic noise compensation in the classification program. Sounds from the same pod/subpod recorded on different dates and from apparently different locations still were judged by the classification system to be similar enough to be put closely together.

In addition, the acoustic patterns of unique, pod-specific calls were compared with recordings of killer whale calls from other unstudied populations. These analyses indicated that there were similarities in acoustic parameters that were common to each group and that allowed them to be distinguished and classified together. Recordings from killer whale populations

in other geographic regions also were analyzed preliminarily and refered to those from known killer whale pods. It was evident that killer whale calls from widely separated populations all had basic sound patterns and similar acoustic structures. Most also appeared to have dominant calls that were likely to be indicative of shared pod-specific calls in each of those areas.

These classification analyses distinguished and sorted the killer whale calls, and provided means for their identification with the shared pod-specific calls of different populations, clans, and pod/subpods of killer whales -- and perhaps even individuals.

Shared pod-specific calls --

To classify the shared pod-specific killer whale calls, the sounds of individuals were selected and analyzed to define sets of AcouStat sound feature statistics for each call. These sets of 120 numerical statistics representing each sound were then organized by database, and compared by statistical analyses. During call classification analysis using a binary tree classifier (S-PLUS or similar analysis), for example, the dominant sound feature statistics used for each decision were identified at each juncture (node) along with the proportion of calls separated at this stage. The analysis progressed with successive divisions in the data based on similarities in the

sound feature statistics, until at the final nodes, all calls were sorted according to their acoustic similarities. During such analysis, one final node was assigned to contain the most variant calls, usually limited to five calls. Although the shared calls of killer whales were highly similar within pod/subpods, there was a small variability that appeared to be the result of individual sound production. This variability in the calls of individuals appeared to account for only about 9% of the calls that were "misclassified" by the analyses. Killer whale calls from different individuals of the same pod/subpod were remarkably alike.

Highly similar pod-specific killer whale calls were analyzed and the classification tree illustrated in Figure 1. Here, 68 calls that were identified by John Ford from his recordings of local Vancouver whales as N4 calls of a variety of members of the "A" clan from four pod/subpods (A05A23, A01A36, A05A08, A04A11) were analyzed. The primary sound feature statistics along with the criterea used for the analysis decisions were identified at each node (Table 1). Calls were sorted into their acoustically similar pod/subpod categories.

The results of the analysis in Figure 1 identified the composition of the five terminal nodes (Table 2). These included four homogenous nodes (4, 5, 13, and 7) and one mixed node (12). Terminal nodes were labeled by the predominant calls

in each one. Node 4 contained all 11 calls of the A05A23 group, and Node 5 had all 23 calls of the A01A36 group. Node 12 had variant calls, two slightly different versions of the call from the A04A11 group and three from the A05A08 group. Node 13 contained 11 calls of the A04A11 group, and Node 7 had 18 calls of the A05A08 group. The mixed node, arbitrarily set to contain five calls, identified slightly variant calls, but also contributed to the indicated analysis error rate, listed as 2/68, with 97% correctly classified according to pod/subpod.

These analyses of shared pod-specific calls from killer whales used AcouStat sound features to relate sounds by their acoustic characteristics and to compare them by statistical analyses. To refine and verify results, such analyses were repeated iteratively with different sets of calls, and a wide variety of call types. Although the killer whale calls had small differences that appeared to be related to distinctions in sound production by individual whales, the similarities among shared calls of the same pod/subpod were consistently sufficient for their use as primary categories for classification of the calls. These natural call categories followed the divisions in calls that had been defined by John Ford through visual inspection of call spectral analyses. The classification analyses agreed with the previously defined call categories.

Calls from unstudied groups --

Calls from unstudied killer whale groups also were analyzed to assess the potential for separating these according to their group associations. Sets of recordings of populations from different geographic regions were analyzed in the same manner. The calls for these analyses were from individual killer whales selected from general recordings of killer whales in Norwegian waters labeled NW, in Cape Cod waters of the northwest Atlantic labeled CC, and some in waters of the northeastern Pacific labeled VN. The classification system consistently distinguished and correctly sorted all but 1 to 2 % of these calls according to their proper group.

In the regression analysis of Figure 2 (S-PLUS), calls were sorted by their AcouStat numeric sound feature statistics (Table 5) which were used as variables for each call. The three geographic regions were used as sorting categories for the analysis (labeled NW, CC, and VN). Calls were divided successfully according to the relative amount of diversity in the AcouStat sound feature statistic variables at each node. The primary sound feature statistic along with the criterea used for these decisions were identified at each node (Table 3).

The results of the analysis are listed in Table 4. All but three of the 213 calls were sorted correctly by region, with the NW and CC calls divided into two subgroups each, a 98.5% correct classification. The analysis separated the calls into six

classification. The analysis separated the calls into six terminal nodes, including four homogenous nodes (2, 27, 14, and 15) and two mixed nodes (12 and 26) that included the two and one call variations, respectively. Terminal nodes were labeled by their predominant calls. One mixed node, arbitrarily set to contain five calls, identified slightly variant calls, but also contributed to the analysis error rate, listed as 3/213.

The classification analysis of Figure 2 placed 91 NW calls in node 2, six slightly different NW and two CC calls in node 12, four CC calls and one VN call in node 26 (the minimum variant set), 74 CC calls in node 27, five different CC calls in node 14, and 30 VN calls in node 15. The differences in calls between areas were sufficient to allow general separation of the calls from the different populations, without other acoustic differentiation. In each region, calls were separated into dominant categories that potentially fit call categories such as those that constitute the pod-specific calls that are recognized for those populations that have been analyzed.

Examples of waveform and spectrographic analysis of such killer whale calls are illustrated in Figures 3 and 4. A typical call from the A clan of Vancouver, BC, is shown in Figure 3. Figure 4 has a somewhat similar call from an unstudied group of killer whales off Cape Cod in the western Atlantic.

SUMMARY

The classification analysis system using AcouStat sound features and statistical analyses to classify and sort sounds was modified for use in sorting the highly similar sounds of killer whales. The AcouStat sound feature statistics are listed in Table 5.

Classification analysis with these statistics provided good sorting of killer whale shared calls with very similar acoustic characteristics, as well as those with distinct sound features.

Highly similar pod-specific calls of killer whales were consistently classified according to their pod/subpod -- demonstrated by analysis of calls from the Vancouver population studied by John Ford (Figure 1, Table 1, Table 2).

The calls from unstudied groups of killer whales from general recordings were consistently sorted according to their group association -- demonstrated by analysis of calls from groups of whales from the U.S. northwest, Cape Cod waters, and Norwegian waters (Figure 2, Table 3, Table 4).

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FIGURE CAPTIONS

Figure 1 --

Killer whale pod-specific N4 call classification tree. The tree analysis sorted 68 type N4 calls from the (John Ford) Vancouver A Clan according to their similarities in acoustic structure, coincident with the pod/subpods of the individual whales producing the calls. This regression analysis (S-PLUS Software) sorted calls using the AcouStat numeric sound feature statistics (Table 5) as variables for each call. The 4 pod/subpods of the individual whales producing these calls were identified during recording by Ford, and were used as sorting categories for the analysis (labeled A05A23, A05A36, A05A11, A05A08). Calls were divided successively according to the relative amount of diversity in the AcouStat sound feature statistic variables at each node (Table 1). The resulting composition of final nodes of this classification is given in Table 2.

Figure 2 --

Classification tree for three sets of unanalyzed killer whale recordings from different geographic regions. The classification analysis sorted 213 calls from individuals in general recordings of whales from Norwegian waters (NW), from Cape Cod waters of the Atlantic (CC), and from the U.S. northwest (VN). The analysis separated these calls according to acoustic similarities common to each region. This regression analysis (S-PLUS) sorted calls used AcouStat numeric sound feature statistics (Table 5) as variables for each call. The three geographic regions were used as sorting categories for the analysis (labeled NW, CC, and VN). Calls were sorted successfully according to the relative amount of diversity in the AcouStat sound feature statistic variables at each node (Table 3). The resulting composition of final nodes of this classification is given in Table 4.

Figure 3 --

Sound waveform and spectrographic analysis of a call produced by a killer whale of the A clan from Vancouver, BC. These calls are composed of variable segments of tonal sequences, pulsed tones, and slower clicks and pulses. Specific call types are repeated in similar ways by most members of a clan, and these calls from different whales can be nearly indistinguishable. Analysis display parameters for this call are given in the margins, including duration of 1.463 sec and frequency range from 156 to 19687 Hz (top of spectrogram). Call recorded by Watkins.

Figure 4 --

Sound waveform and spectrographic analysis of a call produced by a killer whale of a group not as yet analyzed from the waters off Cape Cod in the western Atlantic. Although from very different geographic locations, these killer whales have similar call structures to the others that have been studied, and in preliminary analysis, they appear to have prominent call categories similar to those that make up the distinctive call types of the populations that have been analyzed previously (such as those of the Vancouver whales). Analysis display parameters for this call are given in the margin, including duration of 1.700 sec and frequency range from 160 to 20160 Hz (top of spectrogram). Call recorded by Watkins.

```
TABLE 1 -- data for N4 call classification

(Figure 1)
68 total calls: A05A23=11, A05A36=23, A05A08=21, A04A11=13
5 terminal nodes,    Primary variables:
"ERGtot" "TFMEDr" "UPSfrac" "SWPfrac"
Residual mean deviance:  0.1068 = 6.73 / 63
Misclassification error rate: 0.02941 = 2 / 68

Node 1
 split: root,  n: 68
 proportion:  A01A36=0.3382353, A04A11=0.1911765,
      A05A08=0.3088235, A05A23=0.1617647

Node 2
 split: ERGtot<1.24129e+011
 n: 34,  dev:  42.81
 yval: A01A36
 A01A36=0.6764706, A04A11=0, A05A08=0, A05A23=0.3235294

Node 3
 split: ERGtot>1.24129e+011
 n: 34,  dev:  45.23
 yval: A05A08
 A01A36=0, A04A11=0.3823529, A05A08=0.6176471, A05A23=0

Node 4
 split: TFMEDr<0.149463
 n: 11,  dev:   0.00
 yval: A05A23
 A01A36=0, A04A11=0, A05A08=0, A05A23=1

Node 5
 split: TFMEDr>0.149463
 n: 23,  dev:   0.00
 yval: A01A36
 A01A36=1, A04A11=0, A05A08=0, A05A23=0

node number: 6
 split: UPSfrac<0.409586
 n: 16,  dev:  15.44
 yval: A04A11
 A01A36=0, A04A11=0.8125, A05A08=0.1875, A05A23=0

Node 7
 split: UPSfrac>0.409586
 n: 18,  dev:   0.00
 yval: A05A08
 A01A36=0, A04A11=0, A05A08=1, A05A23=0

Node 12
 split: SWPfrac<0.342105
 n: 5,  dev:   6.73
 yval: A05A08
 A01A36=0, A04A11=0.4, A05A08=0.6, A05A23=0

Node 13
 split: SWPfrac>0.342105
 n: 11,  dev:   0.00
 yval: A04A11
 A01A36=0, A04A11=1, A05A08=0, A05A23=0
```

TABLE 2 --

N4 call classification -- 68 Calls
Composition of terminal nodes in Figure 1

Node	Pod/subpod	Calls in Node	% of Node	% of Total	Call Total
4	A05A23	11	100	100	11
5	A01A36	23	100	100	23
12	A05A11	2	40	18	13
"	A05A08	3	60	35	21
13	A04A11	11	100	82	13
7	A05A08	18	100	65	21

```
TABLE 3 -- Data for Geographic Regions classification
(Figure 2)  213 total calls: 85 CC, 97 NW, 31 VN
6 terminal nodes,    Primary variables:
"MODWmed" "ERGmed" "ERGtot" "ZERnum" "UPSfrac"
Residual mean deviance:  0.06764 = 14 / 207
Misclassification: 0.01408 = 3 / 213

Node 1
 split: root,  n: 213
 proportion: CC=0.399061, NW=0.4553991, VN=0.1455399

Node 2
 split: MODWmed<211.686
 n: 91,  dev:   0.000
 yval: NW
 CC=0, NW=1, VN=0

Node 3
 split: MODWmed>211.686
 n: 122,  dev: 182.500
 yval: CC
 CC=0.6967213, NW=0.04918033, VN=0.2540984

Node 6
 split: ERGmed<1.0876e+008
 n: 87,  dev:  54.440
 yval: CC
 CC=0.9195402, NW=0.06896552, VN=0.01149425

Node 7
 split: ERGmed>1.0876e+008
 n: 35,  dev:  28.710
 yval: VN
 CC=0.1428571, NW=0, VN=0.8571429

Node 12
 split: ERGtot<4.1346e+008
 n: 8,  dev:   8.997
 yval: NW
 CC=0.25,NW=0.75,VN=0

Node 13
 split: ERGtot>4.1346e+008
 n: 79,  dev:  10.730
 yval: CC
 CC=0.9873418, NW=0, VN=0.01265823

Node 14
 split: UPSfrac<0.5214
 n: 5,  dev:   0.000
 yval: CC
 CC=1, NW=0, VN=0

Node 15
 split: UPSfrac>0.5214
 n: 30,  dev:   0.000
 yval: VN
 CC=0, NW=0, VN=1

Node 26
 split: ZERnum<22.5
 n: 5,  dev:   5.004
 yval: CC
 CC=0.8, NW=0, VN=0.2

Node 27
 split: ZERnum>22.5
 n: 74,  dev:   0.000
 yval: CC
 CC=1, NW=0, VN=0
```

TABLE 4 --

Geographic Regions Classification -- 213 Calls
Composition of terminal nodes in Figure 2

Node	Pod/subpod	Calls in Node	% of Node	% of Total	Call Total
2	NW	91	100	93	97
12	NW	6	75	7	97
"	CC	2	25	2	85
26	CC	4	80	5	85
"	VN	1	20	3	31
27	CC	74	100	86	85
14	CC	5	100	6	85
15	VN	30	100	97	31

TABLE 5 --

LIST OF SOUND FEATURE STATISTICS CALCULATED BY ACOUSTAT

Fristrup and Watkins 1992, 1994
(modified 1997 DiMarzio and Watkins)

The AcouStat acoustic sound feature analysis algorithm designed by K. Fristrup (Fristrup and Watkins 1992, 1994). For the killer whale call analyses, AcouStat (written in "C" software format) was used in an MS-DOS environment. AcouStat calculated 120 numerical features, along with additional descriptive information for each sound file. The program sequentially analyzed digital sound files in the WHOI database KAY format (.KAY extension). File names were used as input to AcouStat and the output was up to 120 numerical values representing the acoustic features of each sound file.

Output includes descriptive information for each file:

FN	filename (first 5 characters)
CN	filename (next 3 characters)
LF	low frequency
HF	high frequency
Bsize	dimensions of data
Xsize	FFT size
Olap	overlapping data points for successive FFT's
CS	Duration of file in seconds

Notes:
mode = mode
med = median
upp = upper frequency
sprd = spread
conc = concentration
modw = modewidth
asym = asymmetry

Sound Feature Statistics:

1 NumBlocks number of FFT's required to process data
2 MaxFlat longest signal with minimal change in frequency mode

Amplitude modulation spectra, aggregate energy greater than 50% of total
3 AM5mode
4 AM5med
5 AM5upp
6 AM5sprd
7 AM5conc
8 AM5modw
9 AM5asym

Amplitude modulation spectra, aggregate energy greater than 75% of total
10 AM7mode
11 AM7med
12 AM7upp
13 AM7sprd
14 AM7conc
15 AM7modw
16 AM7asym

Amplitude-Frequency Spectra, aggregate energy greater than 50% of total
17 AFM5mod
18 AFM5med
19 AFM5upp
20 AFM5sprd
21 AFM5conc
22 AFM5modw
23 AFM5asym

Table 5 (continued)

Amplitude-Frequency Spectra, aggregate energy greater than 75% of total
24 AFM7mod
25 AFM7med
26 AFM7upp
27 AFM7sprd
28 AFM7conc
29 AFM7modw
30 AFM7asym

Total Spectrum, aggregate energy greater than 50% of total
31 TSmod5
32 TSmed5
33 TSupp5
34 TSsprd5
35 TSconc5
36 TSmodew5
37 TSasym5

Total Spectrum, aggregate energy greater than 75% of total
38 TSconc7
43 TSmodew7
44 TSasym7

Modal Spectrum, aggregate energy greater than 50% of total
45 MSmod5
46 MSmed5
47 MSupp5
48 MSsprd5
49 MSconc5
50 MSmodew5
51 MSasym5

Modal Spectrum, aggregate energy greater than 75% of total
52 MSmod7
53 MSmed7
54 MSupp7
55 MSsprd7
56 MSconc7
57 MSmodew7
58 MSasym7

59 ERGtot total power

Time-Amplitude, aggregate energy greater than 50% of total
60 ENVmod5
61 ENVmed5
62 ENVupp5
63 ENVdur5
64 ENVconc5
65 ENVmodw5
66 ENVasym5

Time-Amplitude, aggregate energy greater than 75% of total
67 ENVmod7
68 ENVmed7
69 ENVupp7
70 ENVdur7
71 ENVconc7
72 ENVmodw7
73 ENVasym7

Table 5 (continued)

Miscellaneous statistics	
74 MMnum	number of blocks per AM sample point
75 UPSfrac	attack fraction
76 SWPnum	number of dissimilar fmodes
77 UPSfrac	upsweep fraction
78 UPSmean	average of all changes in frequency median
79 SWPabsmag	upsweep absolute magnitude
80 ZERnum	number of adjacent non-zero ss blocks
81 ERGmed	median amplitude
82 ERGcv	amplitude coefficient of variance
83 ERGmxmd	maximum/median amplitude
84 ERGasym	amplitude asymmetry

Deviation in sum-squared difference of ranks from expected value 85
TFMODr time - frequency mode

86 TFMBWr	time - frequency mode bandwidth
87 AFMBWr	amplitude - frequency mode bandwidth
88 TAr	time - amplitude
89 TFMEDr	time - frequency median
90 AFMEDr	amplitude - frequency median

Frequency Mode -- mode, median, spread and asymmetry
91 FMODmod
92 FMODmed
93 FMODsprd
94 FMODasym

Frequency Median -- mode, median, spread and asymmetry
95 FMEDmod
96 FMEDmed
97 FMEDsprd
98 FMEDasym

Spectral Concentration -- mode, median, spread and asymmetry
99 CONCmod
100 CONCmed
101 CONCsprd
102 CONCasym

Mode Width -- mode, median, spread and asymmetry
103 MODWmod
104 MODWmed
105 MODWsprd
106 MODWasym

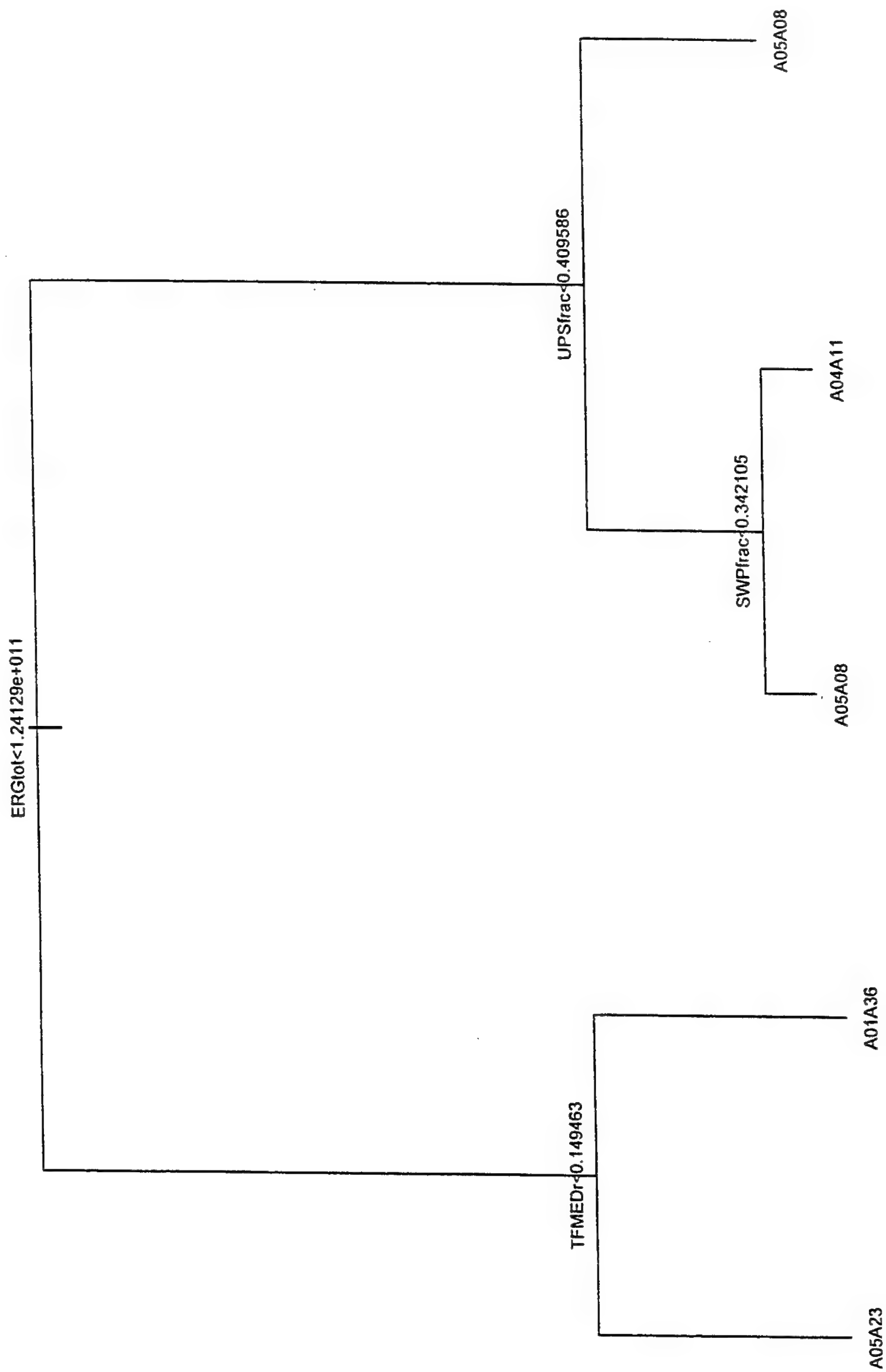
Frequency Spread -- mode, median, spread and asymmetry
107 FSPRDmod
108 FSPRDmed
109 FSPRDsprd
110 FSPRDasym

Deviation of sum-squared difference of ranks from expected value 111
AFSPRDr amplitude-frequency spread
112 FMEDFSPRDr frequency median - frequency spread
113 TFSPRDr time - frequency spread

Frequency Asymmetry -- mode, median, spread and asymmetry)
114 FASYMmod
115 FASYMmed
116 FASYMsprd
117 FASYMasym

Deviation of sum-squared difference of ranks from expected value 118
AFASYMr amplitude - frequency asymmetry
119 FMEDFASYMr frequency median - frequency asymmetry
120 TFASYMr time - frequency asymmetry

Figure 1



ERGtot<1.24129e+011
UPSfrac<0.409586
A05A08
SWPfrac<0.342105
A04A11
A05A08
TFMEDr<0.149463
A01A36
A05A23

Figure 2

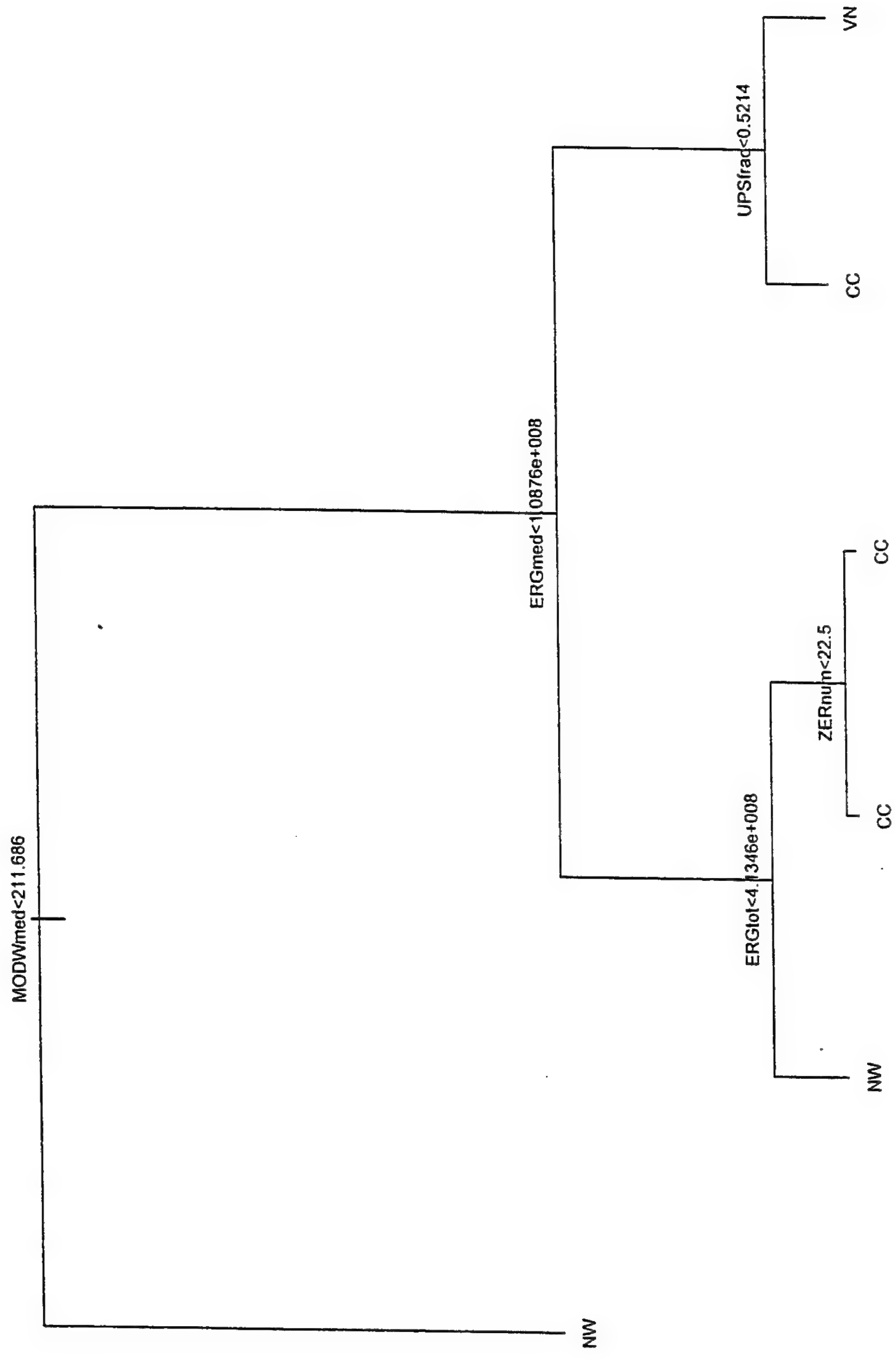

MODWmed<211.686
ERGmed<1.0876e+008
UPSfrac<0.5214
ERGtot<4.1346e+008
ZERnum<22.5
NW
NW
CC
CC
CC
VN

FIGURE 3

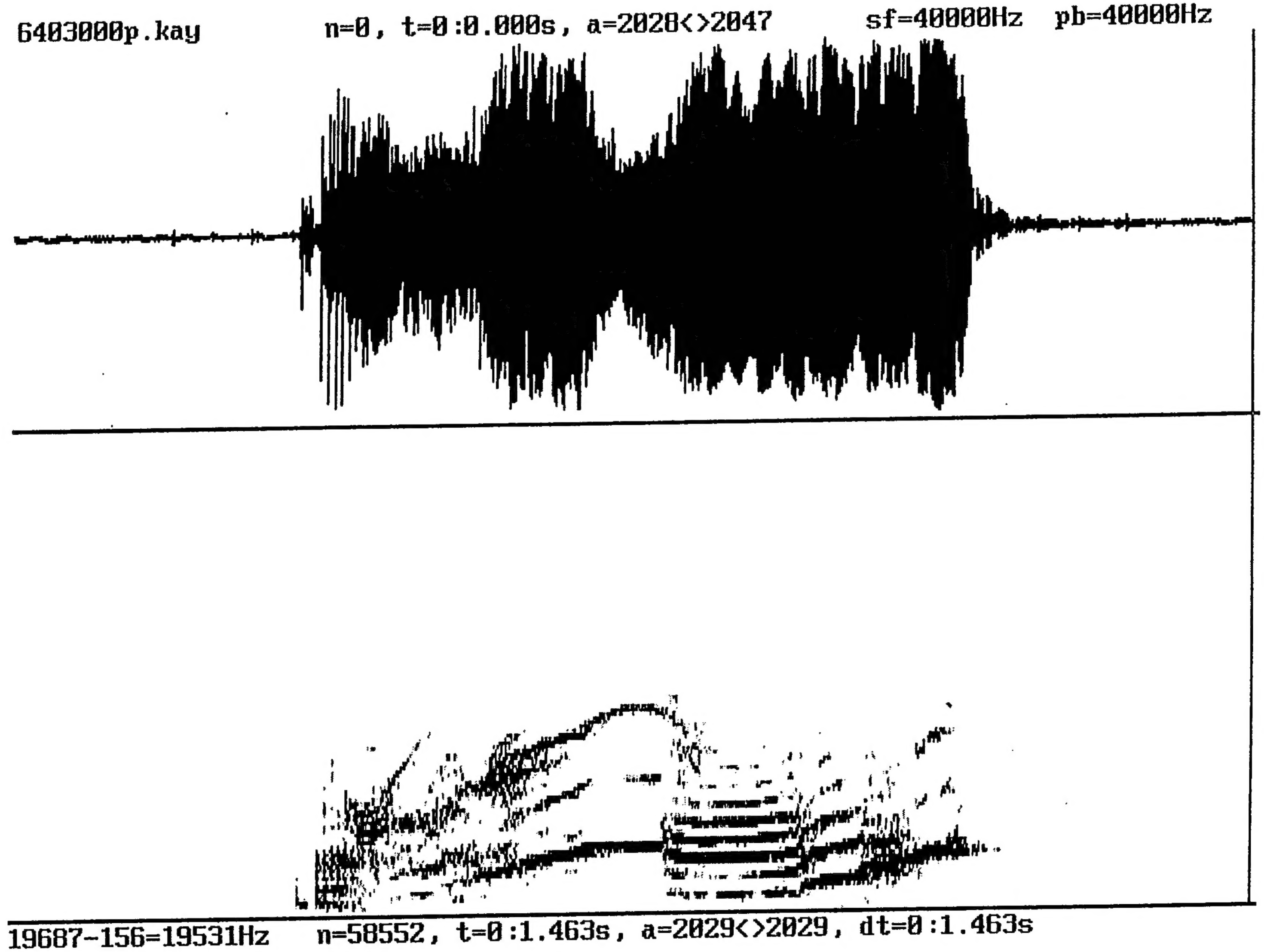
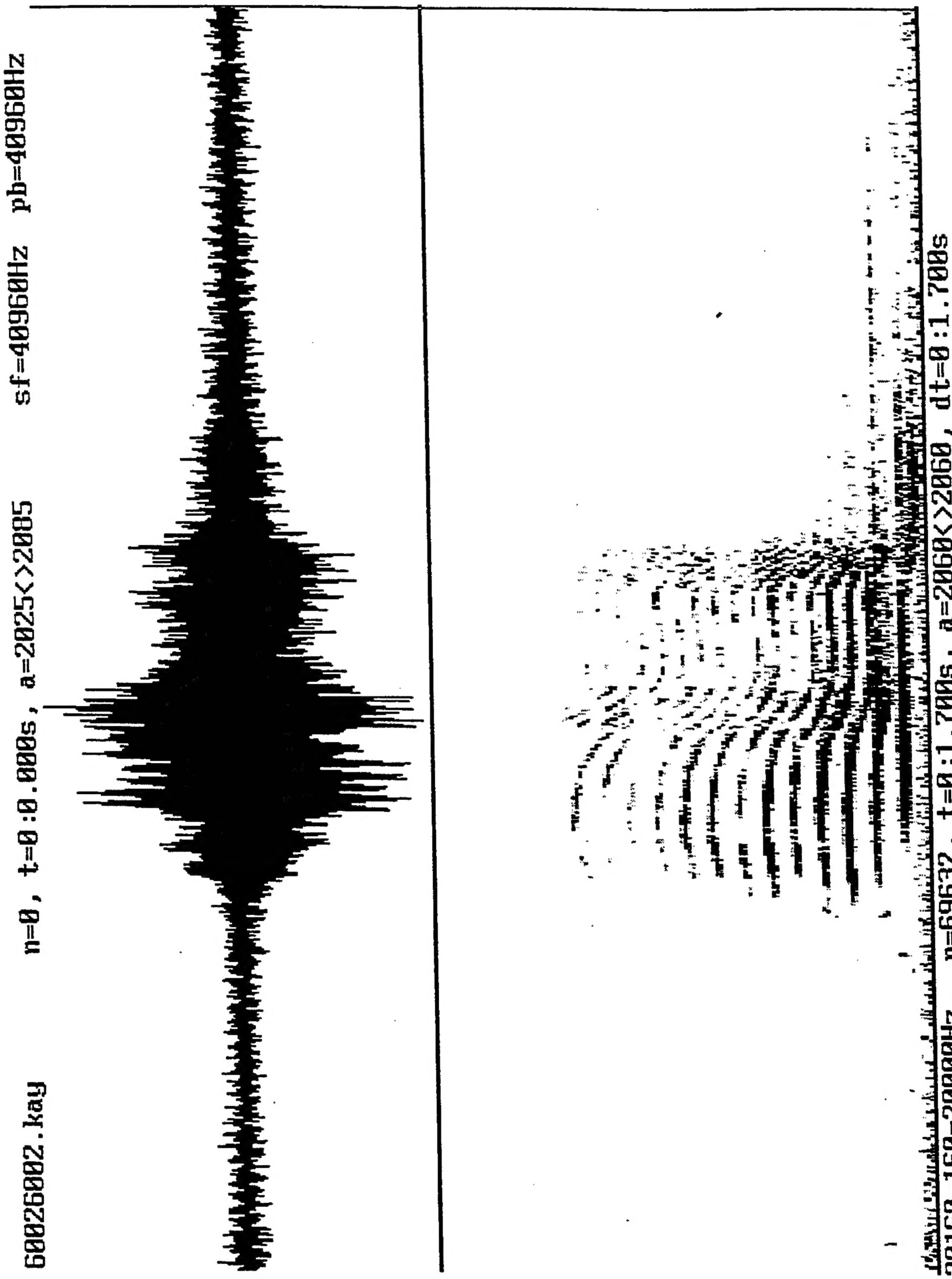

6403000p.kay
n=0, t=0:0.000s, a=2028<>2047
sf=40000Hz pb=40000Hz
19687-156=19531Hz
n=58552, t=0:1.463s, a=2029<>2029, dt=0:1.463s

FIGURE 4


60026002.kay
n=0, t=0:0.000s, a=2025<>2085
sf=40960Hz
pb=40960Hz
20160-160=20000Hz
n=69632, t=0:1.700s, a=2060<>2060, dt=0:1.700s

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16. Abstract (Limit: 200 words)

Calls of killer whales, *Orcinus orca*, were analyzed using computed sound features to classify sound patterns and identify call similarities. Calls were classified and separated according to the pod/family group within clans identified previously by John Ford (U. BC) in the Vancouver whale populations. Acoustic characteristics of the same call type from different individuals were extremely similar, so that discriminating these different sounds was the goal. The WHOI AcouStat program and associated database systems were used to define numerical statistics for each call, and then, these were compared to sort and classify the sounds. The results were in agreement with Ford's descriptions of the calls derived from visual inspection of sound spectrograms of calls. The classification analyses demonstrated that although specific shared calls from different killer whales were much alike, they could be sorted by the pod/subpod of the whales producing the calls. A typical analysis, for example, of the N4 call from Clan A (Vancouver, BC), classified 97% of the calls correctly according to the pod/family of the whales producing the calls. Remaining calls were variant, and likely a result of individual differences in call sounds. Similar classification analysis were tested on unsorted, unalyzed recordings from different populations of whales, and these too could be distinguished, with 98.5% correct separation of the calls.

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Orcinus orca

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